STABILIZATION OF CLAY SOILS BY ELECTRICAL METHODS

WILLIAM B. STEPHENSON

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STABILIZATION OF CLAY SOILS BY ELECTRICAL METHODS

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Lieutenant (j.g.), CEC, USN

Presented as partial fulfillment of the
requirement for the degree of
Master of Civil Engineering
Rensselaer Polytechnic Institute
Troy, New York

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ACKNOWLEDGMENT

The author wishes to thank Professors E. J. Kilcawley and S. V. Best for their help and guidance during the experimental work and subsequent evaluation of results.

LETTER OF TRANSMITTAL

7 Hudson Avenue,
Green Island, New York.
August 30, 1948.

Faculty,
Civil Engineering Department,
Rensselaer Polytechnic Institute,
Troy, New York.

Gentlemen:

As partial fulfillments for the requirements for the degree of Master of Civil Engineering, I have the honor of submitting this thesis for your approval. It is hoped that the results of this investigation will be of value to future investigators.

I should like to express my appreciation for the knowledge and guidance that you have bestowed upon me during my stay at Rensselaer.

FOREWORD

This thesis is a continuation of the thesis presented by Lieutenant W. J. Christensen, CEC, USN, in June 1948.

In the previous experimentation by Lieut. Christensen and myself, many avenues of investigation were opened. Some of them appeared conventional and others completely contrary to existing theories. No attempt can be made to explain these phenomena until much more information is available.

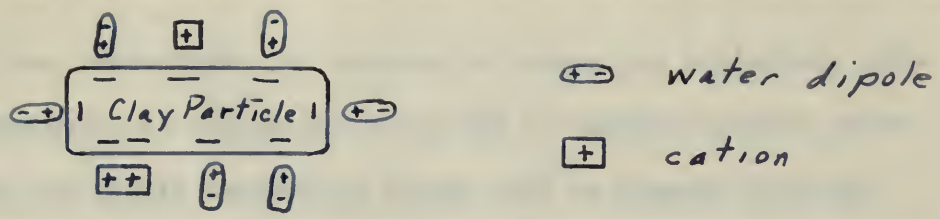
INTRODUCTION

As previous experimentation had given positive results from electrical treatment of clay using aluminum electrodes, it was decided to continue these experiments over a longer period of time to determine what cations were driven off, and the final liquid and plastic limits after treatment. There is one limitation. The cations present in the original clay sample are unknown. However, it seems plausible that should more than one type of cation be present, each type would be replaced in the inverse order of its attraction to the charged clay particle. Since the replaced cations are carried off in the water collected at the cathode, periodic analysis of this water will indicate which cations are replaced.

Further investigation is to be carried on using magnesium electrodes on previously treated clay to determine the effects of this metal both on the cations carried off in the cathode water and the plastic and liquid limits of the clay. The final investigation is to be similar but copper electrodes are to be used on untreated clay.

THEORY

The theory of base cation exchange is based primarily on the Helmholtz concept of the electric double layer around the colloidal particle, which states that "the potential is higher the greater the number of electric charges on the surface and the larger the average distance of the outer layer from the inner". In other words, the clay particle is electro-statically charged either positively or negatively. Assume the particle is negatively charged. The water molecules, being dipoles, are attracted to the particle with their positive end toward the particle. In addition, any cations present will also be attracted to this molecule.

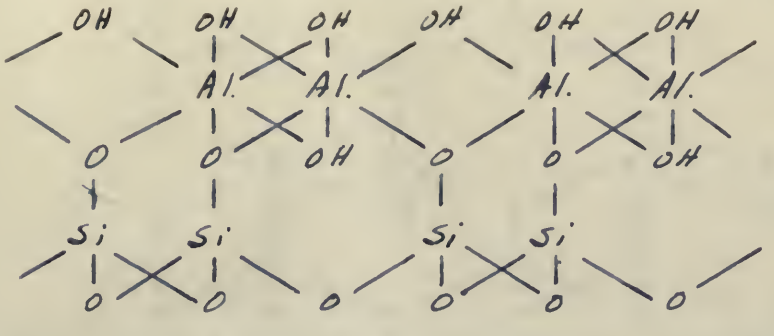


From this we see that multivalent cations will neutralize more of these static charges than the lower valence cations and therefore release some of the adsorbed water.

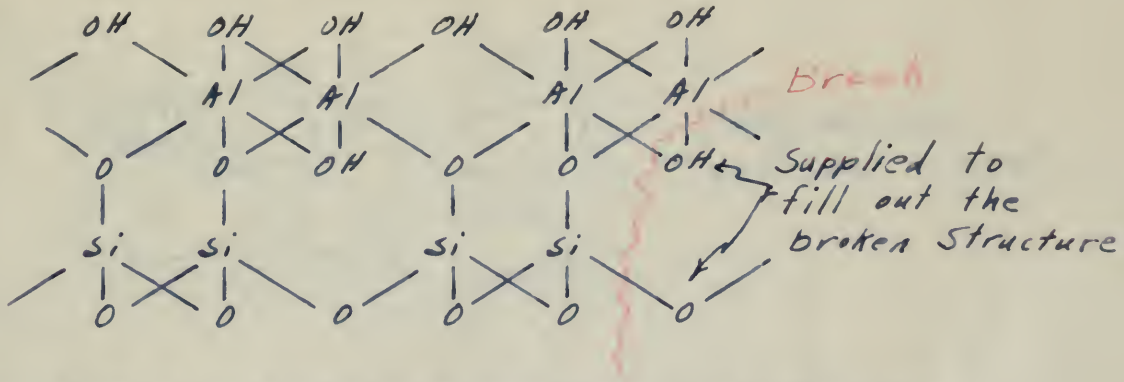
Looking further into the theory, we find two types of adsorbed water. First there is the broken-bond water which is adsorbed through orientation of the water molecules by the free bonds of Al, Si, or O ions on the exposed edges of a broken crystal lattice. This type of adsorption is considered relatively strong. Second, there is planar water which is that adsorbed by the unsaturated valences or free electric fields on the surface of the sheets of the crystal lattice. Such water is loosely held and is easily expelled at low temperatures. This type

of water dominates over the broken-bond form.

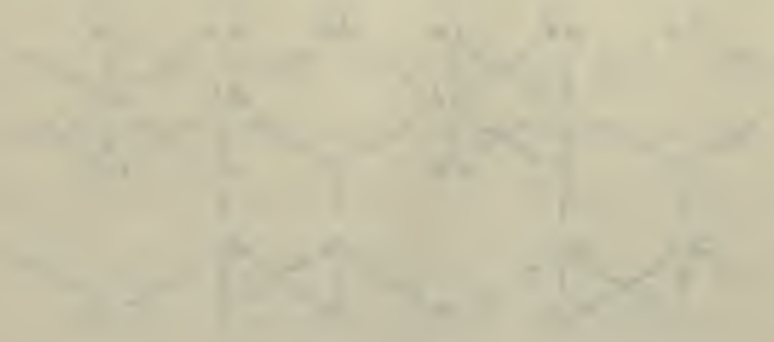
The first type is of the greatest interest in permanent stabilization, for if the broken crystal lattice can be filled out, then the strongly held water can be permanently driven out of the clay. Assume we have a kaolinite clay with a normal crystal lattice as shown.



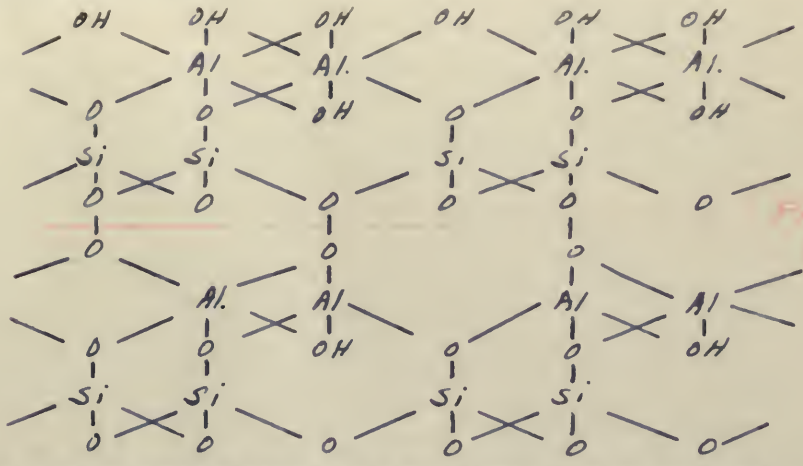
If now, the free bonds where the lattice is broken are satisfied, that is, if the structure is filled out or bonded to another lattice structure, part of the static electrical charge will be removed from the clay particle. This in turn will eliminate the broken-bond water. A possible "satisfied" structure is shown.



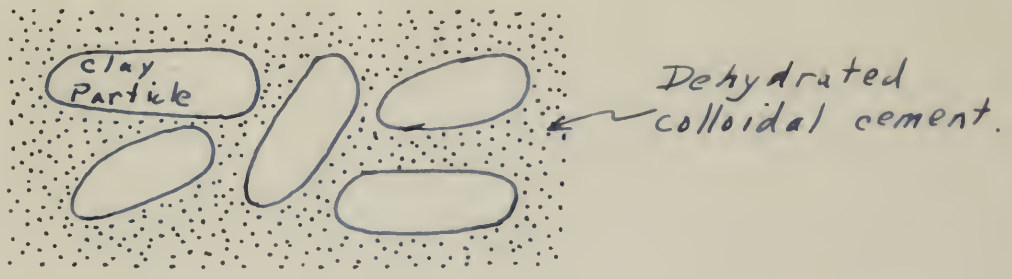
To get rid of the loosely held planar water, it is necessary to link the clay particles together. Complete dehydration is visualized as effecting a union of the clay micelles through oxygen



linkages as water is driven off from the OH groupings in the surface. When this type of cementation takes place, the system is very slowly reversible and the rehydration of clay increases slowly with time.



Still another method can be visualized. If a colloid, such as aluminum hydroxide or iron hydroxide, is dehydrated between the clay particles, the colloid acts as a cementing agent binding the clay particles together. The dehydration of the aluminum hydroxide or iron hydroxide is almost completely irreversible.



In recent experiments, Preece has found indications that clay particles normally charged negatively may become positively charged

when in the influence of an electric field. This brings forth the possibility that anions as well as cations may be involved in stabilization processes.

REPORT

APPARATUS

(a.) Power supply - 110 v. DC, 3300 watts

(b.) Weston DC Ammeter, 25 amp capacity

(c.) Weston DC Voltmeter, 150 volts capacity

(d.) Test boxes 2' by 6" by 12" inside dimensions

(e.) Standard liquid limit apparatus

(f.) Graduated cylinders, 1000 ml.

(g.) Aluminum electrodes, 0.102 ga. annealed

(h.) Magnesium electrodes

(i.) Copper electrodes

PROCEDURE FOR EXPERIMENTS 1, 2, and 3

The clay sample was mixed with water to form a thick slurry, and then poured into the test boxes around perforated electrodes which served also as well points. The electric voltage was applied to the electrodes and maintained as nearly constant at 110 v as possible.

Water which migrated to the cathode was continuously drained off and collected for determination of cation content. Fresh water was introduced at the anode to maintain an abundant supply at all times. Treatment was intermittent of necessity but the clay was never allowed to dry out.

At the completion of the experiment, the liquid and plastic limits of samples from both the anode and cathode were obtained.

The procedure for determination of cations present in the water sample is as follows:

1. Measure out 50 ml. sample.
2. Make alkaline with NH_4OH. A white precipitate shows presence of aluminum cations. If precipitate forms remove by filtration.
3. Neutralize to litmus with HCl. Add ½gm. of ammonium oxalate. Make solution alkaline with NH_4OH. A white precipitate shows presence of calcium. If precipitate forms remove by filtration.
4. Add 1 gm. of ammonium-acid-phosphate $(NH_4)_2HPO_4$ plus 1/5 of the volume of NH_4OH.

Allow to stand one hour. A white precipitate shows presence of magnesium. If precipitate forms, remove by filtration.

5. Using the filtrate from the above test, a standard qualitative analysis for potassium and sodium cations was made. In addition, a flame test for these two cations was made.

The PH of all samples was determined by the Beckman PH meter before chemical analysis.

EXPERIMENT 1

In this experiment, perforated aluminum cylinders of about two inches diameter, fourteen inches long, and spaced twelve inches apart were used for electrodes. The clay slurry was poured around them to a depth of about ten inches. A drain hole was located below the center of the cathode.

After the current began to flow and the water started migrating to the cathode, fresh water was added at the anode to keep an abundant supply there at all times. The water collected at the cathode was analyzed about every twenty hours to determine the cation content and the PH. For about the first one hundred fifty hours the only cation present was calcium, which was quite plentiful. From about one hundred fifty hours to about two hundred twenty hours, a small amount of magnesium appeared. The calcium remained about the same. From two hundred twenty hours to two hundred forty hours, only calcium was present. At two hundred forty hours, the experiment was discontinued.

There were several things of note. First, in spite of the water supply at the anode, the clay shrank in volume causing shrinkage cracks which had to be filled in to keep the current flowing. As the experiment progressed, the clay became firmer, going into the plastic state. Second, toward the end of the experiment, no gas was given off at the anode but hydrogen still appeared at the cathode. Third, at the end of the experiment, the clay adjacent to the anode and cathode had a very granular appearance and feeling. Fourth, the aluminum electrodes had almost doubled their original weight due to scale which had formed on them.

This scale consisted of both aluminum and calcium compounds but predominantly of aluminum compounds. Last, the water drained off at the cathode was very basic with a PH starting at 10.03 and ending up at 11.87.

The plastic and liquid limits of the clay were both increased as shown below:

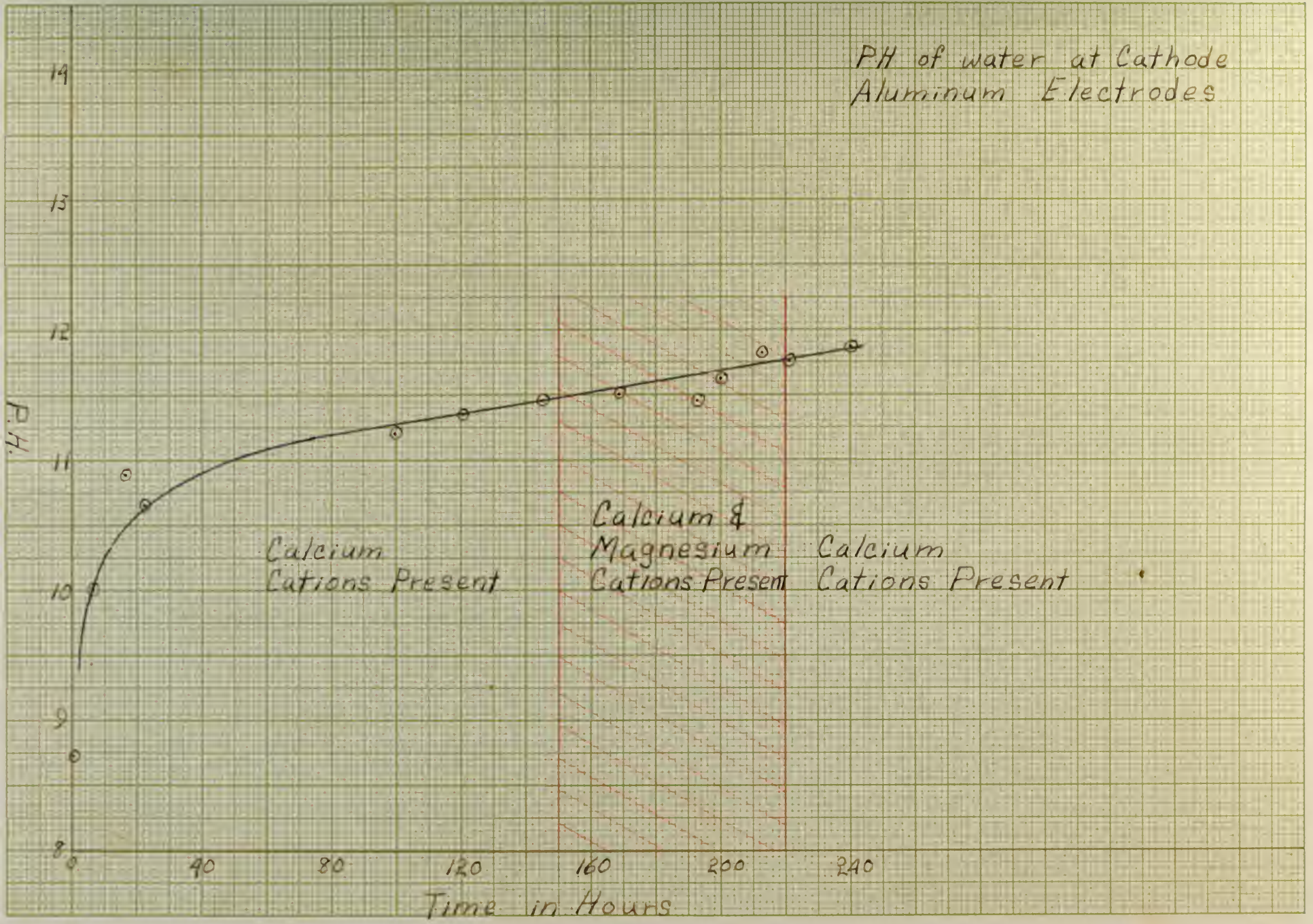
At the anode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	25.7%	38.5%

At the cathode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	24.9%	40.3%

ALUMINUM


PH of water at Cathode
Aluminum Electrodes
14
13
12
11
10
9
8
P.H.
Calcium
Cations Present
Calcium &
Magnesium
Cations Present
Calcium
Cations Present
0
40
80
120
160
200
240
Time in Hours

EXPERIMENT 2

The clay used in experiment 1 was air dried, pulverized, and mixed with water to form a thick slurry. Perforated cylindrical magnesium electrodes spaced twelve inches apart were placed into the test box and the clay poured around them. The current was turned on and fresh water supplied to the anode while water driven off was collected at the cathode. This water was analyzed for cation content at frequent intervals. The experiment lasted for forty-four hours with about one amp. of current flowing.

In this experiment the water supply at the anode was controlled more carefully and the top surface of the clay was frequently sprinkled to compensate for evaporation. Still the clay decreased in volume and shrinkage cracks appeared. However, the consolidation took place much more rapidly than in experiment 1.

Here again there are several things of note. First, throughout this experiment, hydrogen was given off at the cathode but no gas appeared at the anode. Second, the anode was eaten away but the cathode was untouched. Third, aluminum compounds were deposited at the anode. Last, the clay adjacent to the anode and cathode displayed a grainy texture.

The plastic and liquid limits of the clay were both increased as shown below:

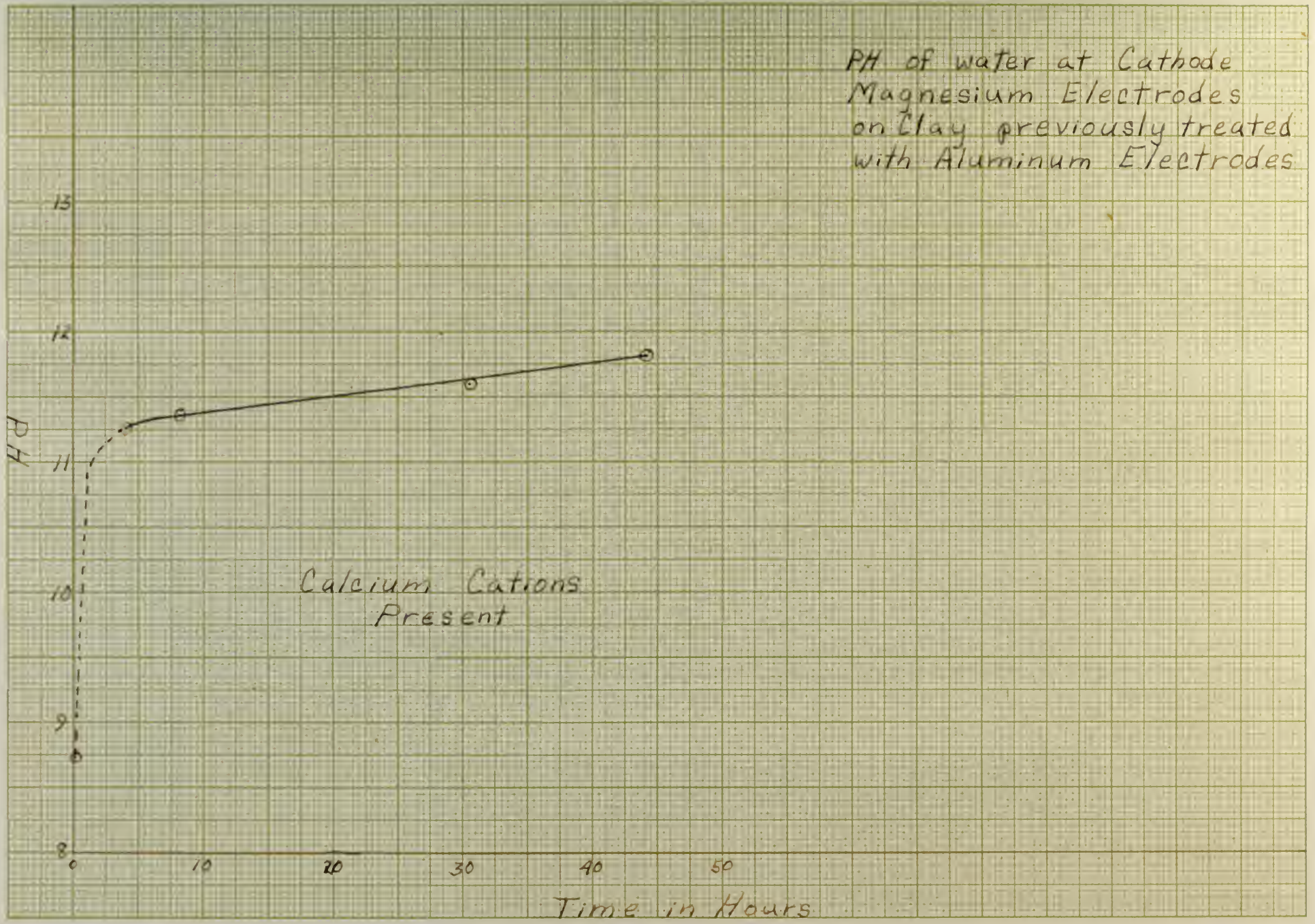
At the anode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	24.5%	38.5%

At the cathode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	33.0%	53.7%

ANODE
CATHODE
MAGNESIUM


PH of water at Cathode
Magnesium Electrodes
on Clay previously treated
with Aluminum Electrodes
13
12
11
10
9
8
PH
Calcium Cations
Present
0
10
20
30
40
50
Time in Hours

EXPERIMENT 3

Perforated cylinders of annealed copper used as electrodes were placed twelve inches apart in the test box. A thick slurry of the original untreated clay was poured around them to a depth of about ten inches. The current was turned on and water was supplied to the anode. The water driven off at the cathode was collected and tested periodically. Throughout this experiment (forty six hours), hydrogen was given off at the cathode and a gas which had the odor of hydrogen sulphide was given off at the anode.

After several hours of treatment, the water at the anode became greenish blue in color and was acid with a PH as low as 5.0. Since fresh water was added at the anode, this PH varied.

After completion of this experiment, the electrodes were removed. The cathode was untouched but the anode was badly eaten away. The metal remaining was deep red in color and resembled red copper oxide. The clay at the anode was greenish in color except for the thin cylinder adjacent to the anode, which was deep red in color. At both electrodes the clay was of granular consistency.

The PH increased from 10.05 to 11.2 over a period of about forty hours.

The liquid and plastic limits increased as shown below:

At the anode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	26.8%	39.5%

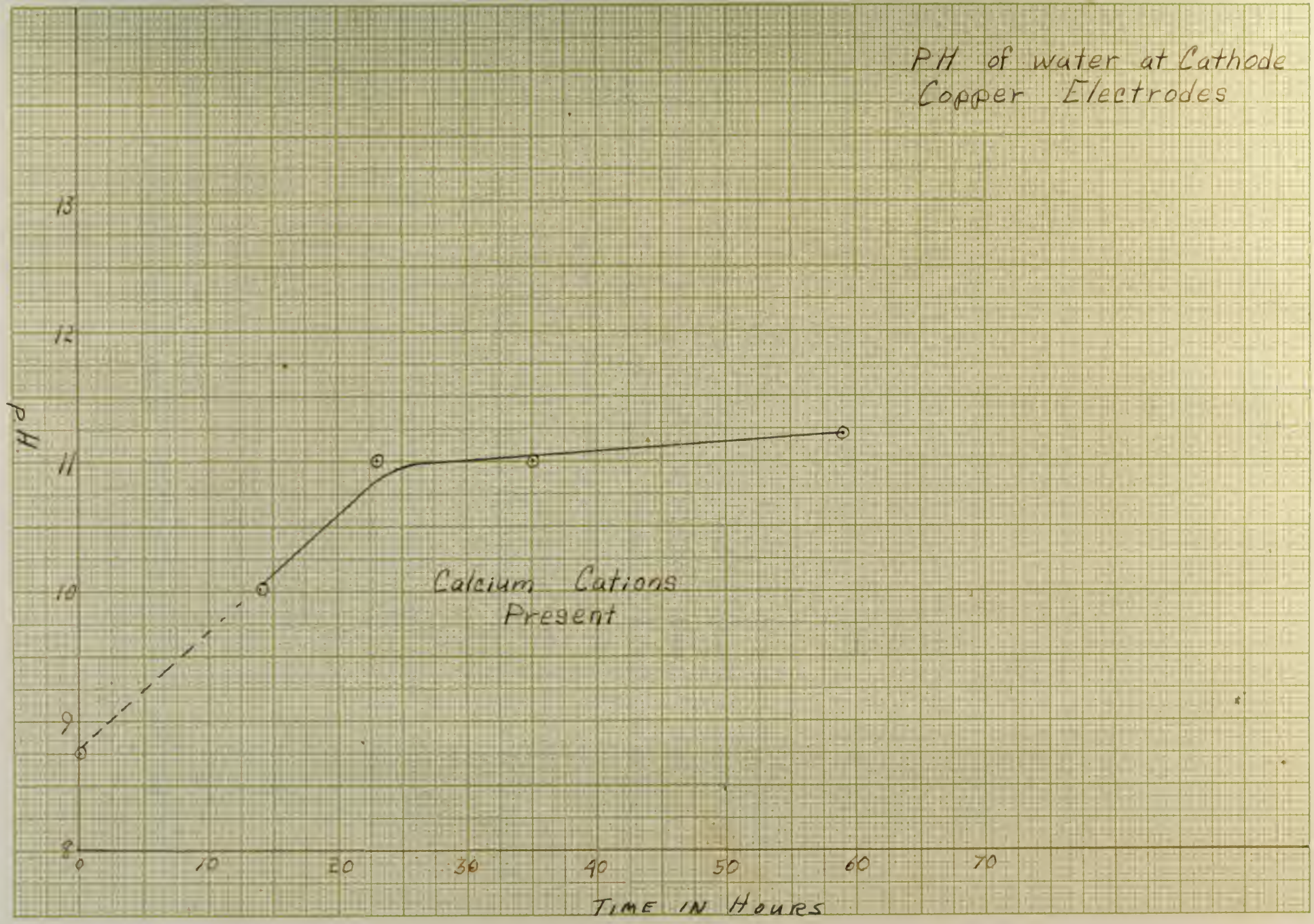
At the cathode:

	Plastic limit	Liquid limit
original clay	21.4%	31.2%
treated clay	41.2%	56.5%

[illegible]

[illegible] [illegible] [illegible] [

ANODE
CATHODE
COPPER


PH of water at Cathode
Copper Electrodes
13
12
11
10
9
8
PH
Calcium Cations
Present
0
10
20
30
40
50
60
70
TIME IN HOURS

CONCLUSIONS

The object of this series of experiments was to determine the cations driven off and the order in which they came off. In the first experiment, calcium cations were driven off first and later magnesium cations. In the second and third experiments, only the calcium cations were driven off. Little, if any, indication of the relative order of replacements of cations can be determined from these results. Indications are that this clay is saturated with calcium cations.

There are several phenomena which were apparent in each of the preceding experiments, some of which may tie in together. It is the author's opinion that they do.

Although the liquid and plastic limits of the clay were increased at both the cathode and the anode, the greatest increase by far was at the cathode. Coupled with this is the fact that there is a high concentration of OH ions at the cathode. This seems to indicate that the OH ions may in some way cause a change in the clay structure. In addition, a strong concentration of calcium was also present at the cathode. Here we have the factors which could cause the changes in the clay as indicated on pages 7, 8, and 9 of this work.

There is another interesting phenomenon which could tie in with those above. During almost all of the experimental work, little or no oxygen was observed coming off at the cathode. This may mean that the oxygen combined with the metal of the anode to form a metallic oxide, or it may have entered into the lattice structures of the clay. It is possible that both may occur.

Contrary to the hypothesis set forth by Lt. Christensen that the

stabilization takes place primarily by exchange of multivalent cations for cations of lower valence, it is felt that little, if any, stabilization is due to this. In an attempt to evaluate the results of these experiments and previous work by others, the following hypothesis of what takes place in the electrical treatment of this clay is submitted.

The electric current passing through the water adsorbed on the clay causes electrolysis of the water resulting in oxygen and hydrogen ions. Part of the oxygen freed in this manner finds its way to the anode where it oxidizes the metal of the anode. Another part may unite with the calcium ions released from the clay particles by the electric current which has partially neutralized the charge on the clay particle. This calcium oxide in the presence of water forms the calcium hydroxide which was present in all test samples. The calcium hydroxide is fairly insoluble and some of it precipitates out between the clay micelles acting as a weak cementing material. Still another part, if in ionic form, may be bonded into the lattice structure to fill out broken lattices.

Some of the hydrogen thus liberated passes off as a gas at the cathode. Some of it remains partially united with oxygen to form an hydroxl ion which may also attach itself to the clay micelles to fill out the lattice structure. In the case of the aluminum cathode, it may be assumed that some of the aluminum is combined with the hydroxl ion to form aluminum hydroxide which was found around the cathode. In the cases of both copper and magnesium, no such action took place.

It is felt that the increase in the liquid and plastic limits of clay is due primarily to three factors.

First by filling out broken lattice structures, the broken-bond water, which is bonded so tightly that it cannot be driven off at 120°F. and therefore does not show up in the moisture content of the clay, is released from the clay. This water provided part of the adsorbed film and its loss requires more planer water to obtain the same liquid and plastic limits.

Second, the forces produced by the flow of electric current may split the fundamental structural units into sheets or break them transversely, thereby creating additional surface forces which demand water (dipole) to satisfy. This additional water partially accounts for the increased liquid and plastic limits.

Third, the cementing material deposited between the clay particles, being a colloid, also has an affinity and demand for adsorbed water. This too adds to the increased water required to reach the liquid and plastic limits.

It is impossible to tie the results down to anything more than a hypothesis until the structure of the clay before and after treatment can be accurately determined. No attempt was made to evaluate these results by Jenny's Hypothesis because nothing is known about this clay structure or the adsorbed ions.

APPENDIX

EXPERIMENT 1

Sample	V	I	Time(hrs.)	PH	Al	Ca	Mg	Na *	K
1	110	1.0	0	8.72	---	Trace	---	Trace	---
2	110	.9	6	10.03	---	Present	---	Trace	---
3	110	.6	17	10.88	---	Present	---	Trace	---
4	110	.4	23	10.65	---	Present	---	Trace	---
5	110	0.7	99	11.20	---	Present	---	Trace	---
6	113	0.5	121	11.35	---	Present	---	Trace	---
7	113	0.6	145	11.45	---	Present	Trace	Trace	---
8	113	0.5	169	11.50	---	Present	Present	Trace	---
9	110	0.6	193	11.47	---	Present	Present	Trace	---
10	110	0.7	200	11.62	---	Present	Present	Trace	---
11	110	0.6	213	11.82	---	Present	Present	Trace	---
12	113	0.6	221	11.75	---	Present	Trace	Trace	---
13	113	0.7	240	11.87	---	Present	Trace	Trace	---

* Presence of sodium indicated in flame test only.

Deposits at Anode.

Al	Ca	Mg	Na	K
Present	Present	None	None	None

Deposit was a soft white powdery substance reported by other experimenters as Bauxite.

Deposits at Cathode.

Al	Ca	Mg	Na	K
Present	Present	None	None	None

Deposit was a hard grey scale surrounded by soft jelly-like aluminum hydroxide.

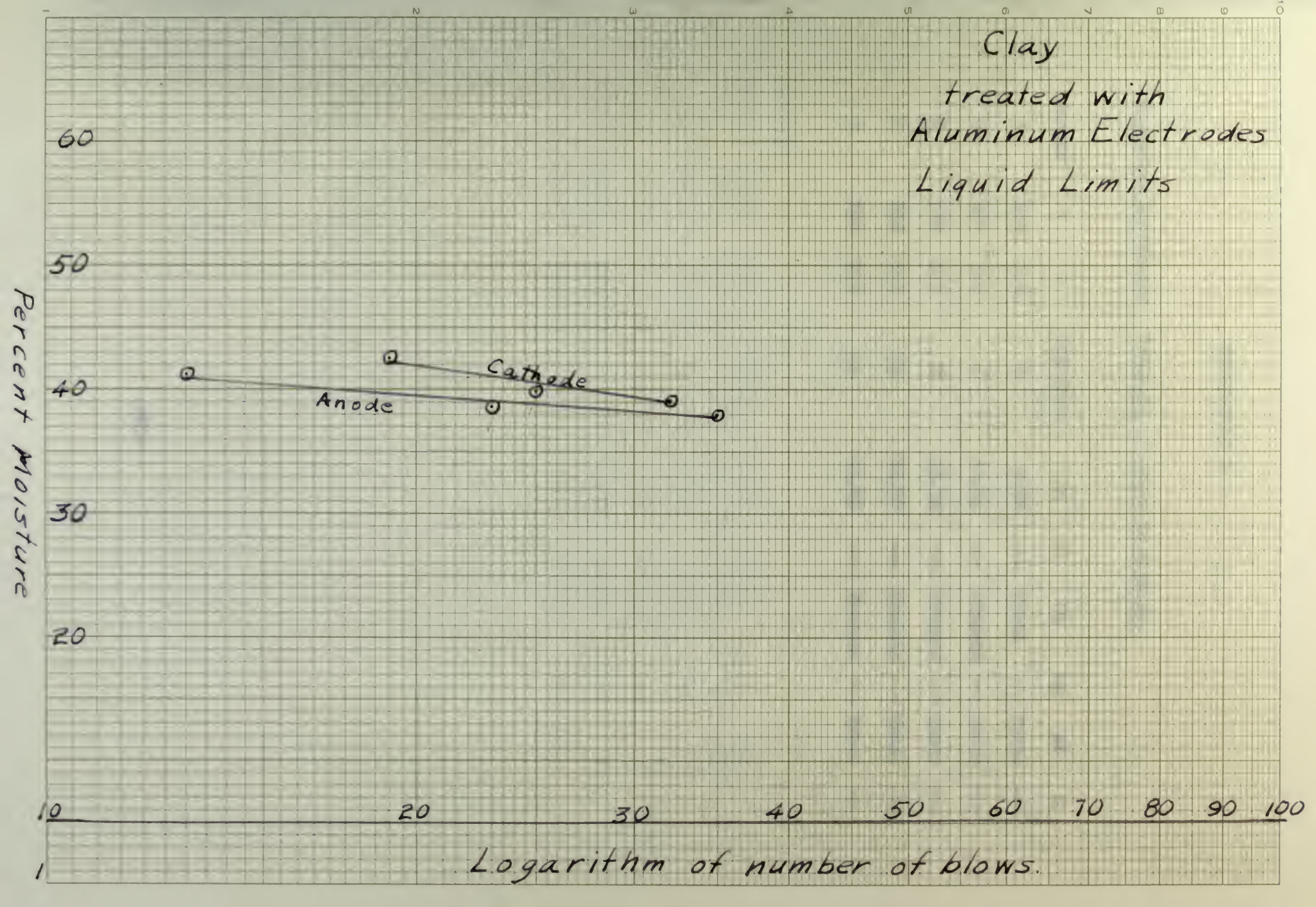
Liquid and Plastic Limits

ANODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
1	18.5240	25.5791	23.5140	4.9900	2.0651	41.3	13	38.5%
2	12.7668	18.3444	16.7890	4.0222	1.5554	38.7	23	
3	12.1154	18.0559	16.4465	4.3311	1.6094	38.0	35	
4	12.9975	17.8705	16.8737	3.8762	0.9968	25.7% = P.L.		

CATHODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
5	12.1870	17.1634	15.6715	3.4845	1.4919	42.8	19	40.3%
6	11.5646	17.2536	15.6552	4.0906	1.5984	39.0	32	
7	11.8174	18.6766	16.7312	4.9138	1.9454	39.6	25	
8	12.2686	16.4713	15.6136	3.3450	0.8577	24.9% = P.L.		


Clay
treated with
Aluminum Electrodes
Liquid Limits
60
50
40
30
20
Percent Moisture
Cathode
Anode
10
20
30
40
50
60
70
80
90
100
1
Logarithm of number of blows.

EXPERIMENT 2

Magnesium Electrodes - Analysis of water at cathode.

Sample	V	I	Time(hrs.)	PH	Al	Ca	Mg	Na	K
1	110	1.0	0	8.72	---	Trace	---	Trace	---
2	110	1.0	4	11.24	---	Present	---	Trace	---
3	110	0.9	8	11.34	---	Present	---	Trace	---
4	110	0.8	33	11.57	---	Present	---	Trace	---
5	110	0.8	44	11.83	---	Present	---	Trace	---

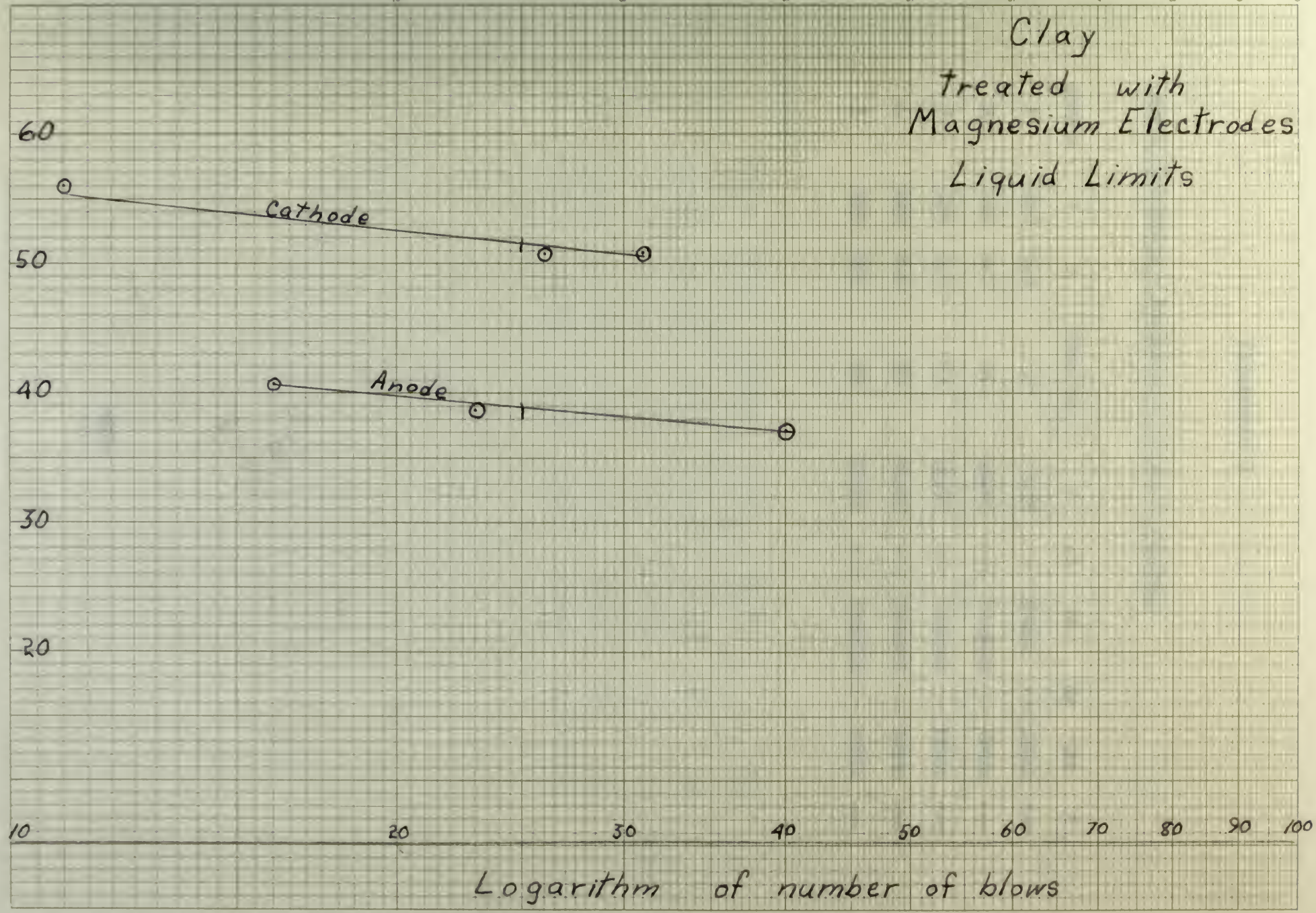
Liquid and Plastic Limits

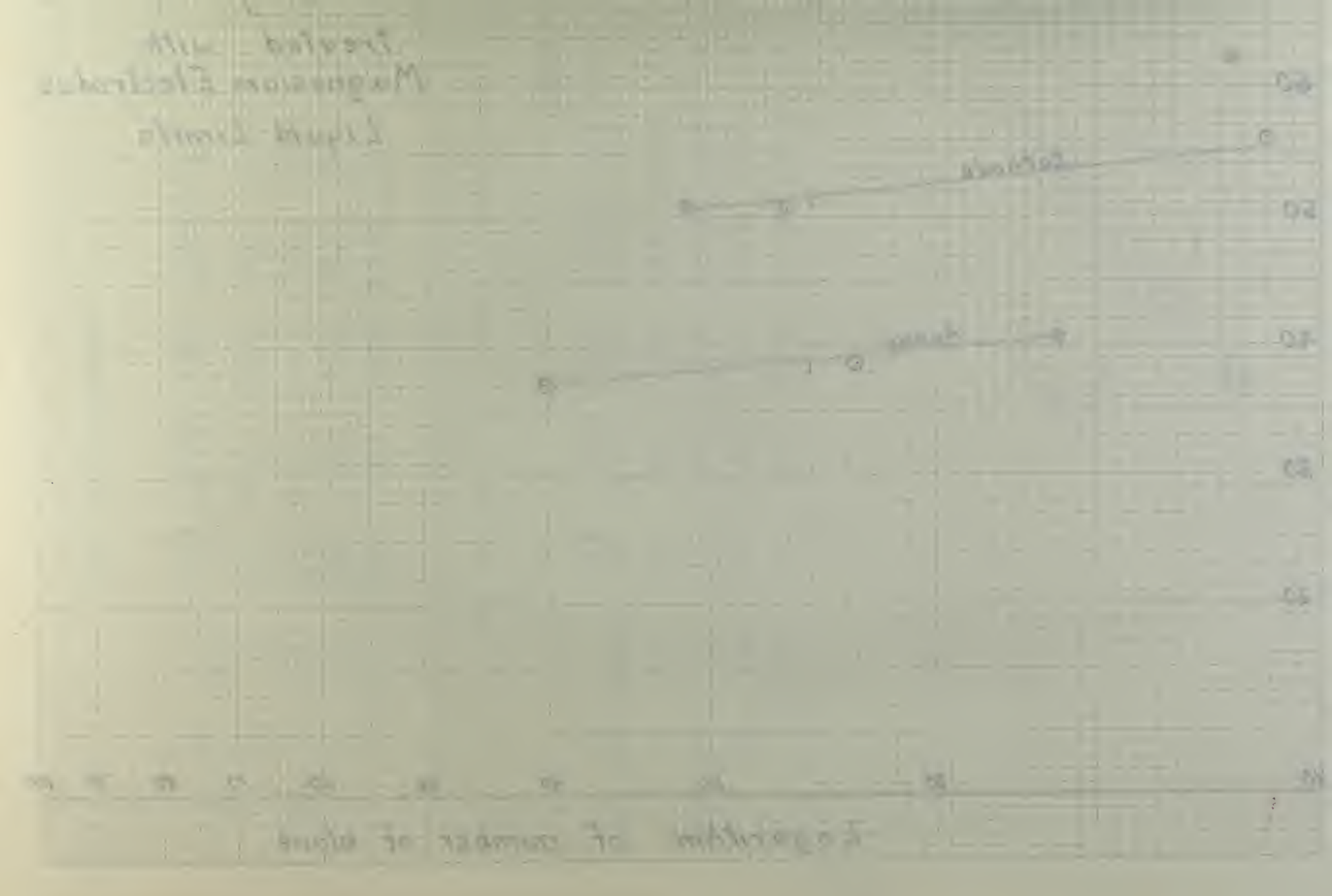
ANODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
9	12.4744	17.3481	16.0323	3.5579	1.3158	37	40	
10	19.2157	27.6597	25.2401	6.0244	2.4196	40.2	16	38.5%
11	12.8501	17.6515	16.3272	3.4771	1.3243	38.1	23	
12	19.6940	26.7873	25.3897	5.6957	1.3976	24.5% = P.L.		

CATHODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
13	20.1950	27.7202	25.1850	4.9900	2.5352	50.8	32	
14	19.8453	27.2548	24.6417	4.7964	2.7131	56.5	26	53.7%
15	19.7224	27.9357	24.9843	5.2619	2.9514	56.1	12	
16	19.6261	24.1851	23.0551	3.4285	1.1300	33% = P.L.		


Clay
Treated with
Magnesium Electrodes
Liquid Limits
Cathode
Anode
60
50
40
30
20
Percent Moisture
10
20
30
40
50
60
70
80
90
100
Logarithm of number of blows



EXPERIMENT 3

Copper Electrodes - Analysis of water at cathode.

Sample	V	I	Time(hrs.)	PH	Al	Ca	Mg	Na	K
1	110	1.0	0	8.72	---	Trace	---	Trace	---
2	110	0.7	14	10.05	---	Present	---	Trace	---
3	110	0.7	23	11.00	---	Present	---	Trace	---
4	110	0.6	35	11.05	---	Present	---	Trace	---
5	110	0.6	58	11.20	---	Present	---	Trace	---

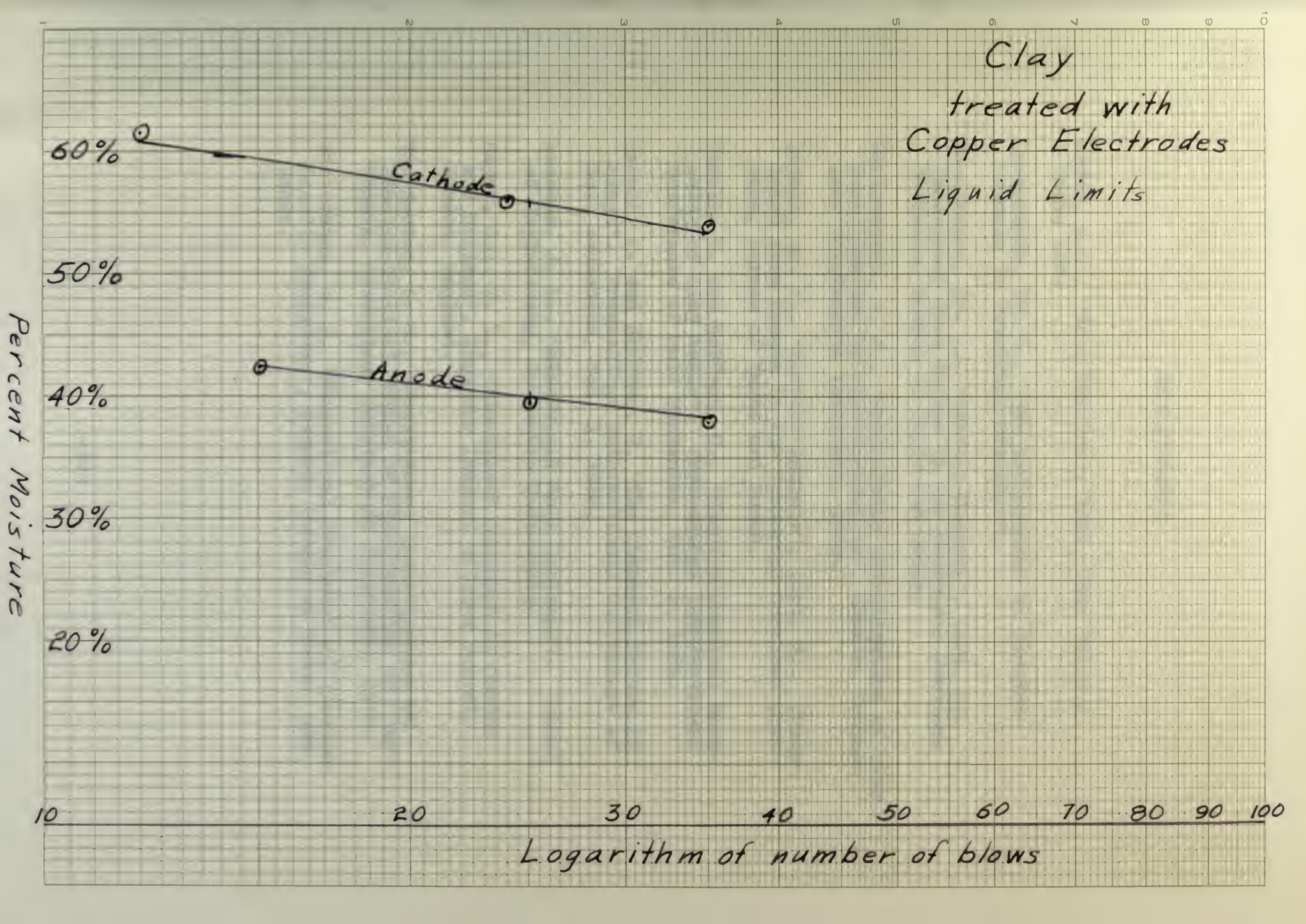
Liquid and plastic limits

ANODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
21	11.5646	17.2564	15.5510	3.9864	1.7054	42.2	15	
22	11.8174	16.7766	15.3738	3.5564	1.4028	39.4	25	39.5%
23	12.4744	18.2754	16.6773	4.2029	1.5981	38.0	35	
24	12.1870	16.2765	15.4181	3.2311	0.8584	26.8% = P.L.		

CATHODE

Sample	Wt.of Cont.	Cont.& Wet Clay	Cont.& Dry Clay	Wt.of Dry Clay	Wt.of Water	% Moist.	No. Blows	L.L.
17	12.7668	17.1881	15.6351	2.8683	1.5530	54.1	35	
18	12.1154	16.2836	14.7859	2.6705	1.4977	56.0	24	56.5%
19	12.2686	17.2946	15.3697	3.1011	1.9249	62.0	12	
20	12.9975	16.6557	15.5859	2.5884	1.0648	41.2% = P.L.		


Clay
treated with
Copper Electrodes
Liquid Limits
Cathode
Anode
60%
50%
40%
30%
20%
Percent Moisture
10
20
30
40
50
60
70
80
90
100
Logarithm of number of blows

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